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Layered Manufacturing: Challenges and Opportunities

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ABSTRACT

Layered Manufacturing (LM) refers to computer-aided manufacturing processes in which parts are made in sequential layers relatively quickly. Parts that are produced by LM can be formed from a wide range of materials such as photosensitive polymers, metals and ceramics in sizes from a centimeter to a few meters with sub-millimeter feature resolutions. LM has found use in diverse areas including biomedical engineering, pharmaceuticals, aerospace, defense, electronics and design engineering. The promise of LM is the capability to make customized complex-shaped functional parts without specialized tooling and without assembly. LM is still a few years away from fully realizing its promise but its potential for manufacturing remains high. A few of the fundamental challenges in materials processing confronting the community are improving the quality of the surface finish, eliminating residual stress, controlling local composition and microstructure, achieving fine feature size and dimensional tolerance and accelerating processing speed. Until these challenges are met, the applicability of LM and its commercialization will be restricted. Sustained scientific activity in LM has advanced over the past decade into many different areas of manufacturing and has enabled exploration of novel processes and development of hybrid processes. The research community of today has the opportunity to shape the future direction of science research to realize the full potential of LM.

INTRODUCTION

Metallic parts are made by one of several technologies, machined from the bulk, cast in a mold and densified in a HIP. Ceramic parts are made by sintering powder compacts, plastic parts by injection molding. Metallic, ceramic or plastic parts can also be made by layered manufacturing. Layered Manufacturing (LM) refers to building a three-dimensional object layer-by-layer, with the architecture of each layer dictated by a CAD drawing. The form is made without support, hence the technology is also known as Solid Freeform Fabrication (SFF). The part could be a solid model designed to serve as a visualization tool in the design of a component, a device or a system. The part could be a functional part, having the same attributes as one made conventionally. The foremost advantage of LM is the ability to make a prototype fairly rapidly, hence the term Rapid Prototyping (RP) is also applied to this technology. In fact, it is in the area of RP that the technology has seen most commercialization. Design engineers and course instructors routinely utilize RP machines for design and instruction. A significant body of research and development work has taken place in LM/SFF/RP over the last 15 years. Today, it can be considered a mature science. Technological maturity is on the horizon. During this period of time, a myriad of techniques has sprouted, driven by the need to fabricate parts from a variety of materials and for a variety of applications. Some methods have achieved commercial status, having graduated from the university level, others are in various stages of research. However, the most pressing question today is whether LM has achieved the status of a viable manufacturing alternative. Will it achieve the same standing as CNC machining? Will it be able to produce parts

and components that can be inserted without qualification into service? The intent of this paper is many-fold. However, it will not try to answer the above questions. This paper will briefly describe the LM principle and the various techniques that have sprouted. It will list the scientific and processing challenges and how they are being met. It will highlight the promise of LM and identify a few success stories. It will talk about scientific opportunities for the technology.

LAYERED MANUFACTURING

"From Art to Part", that is the slogan for LM. The LM process is illustrated in Figure 1. We start with a rendition of the object in a *CAD system*. The CAD drawings (e.g., Unigraphics, CATIA or ProEngineer) are sent to an automated *process planner* in a data exchange format. In the process planner, the CAD model is "sliced" by one of many slicing programs. Depending upon the geometry of the slice, the process planner also determines motion control trajectories for each slice. These trajectories are fed into an *automated fabrication machine* where the slice is traced or deposited on a suitable substrate, guided by the x-y motion of the build platform or that of the deposition head. Alternatively, the slice is patterned on the substrate using masks. Similarly, the next slice is formed after incremental displacement of the platform in the build or z-direction. Sequential stacking of such slices results in the building of a 3D object. In short, a *computerized solid model* is directly converted to a *physical solid model.*

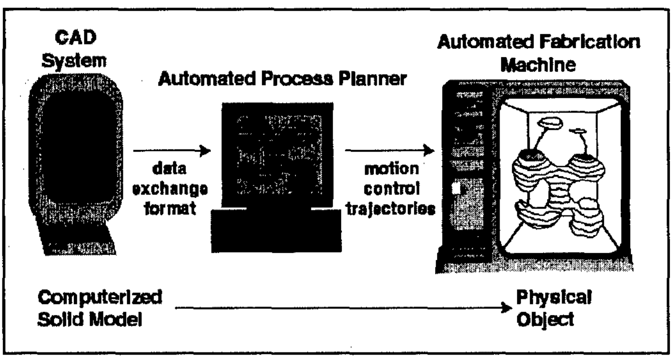

Figure 1. Schematic representation of the LM process.

LM is mainly an additive process. Each slice is added to the previous slice. While most of LM fabrication is usually done with single material processing, multi-material processing is also being developed, especially when support structures are necessary for complex geometries such as internal cavities and overhangs. In fact, most deposition techniques allow for the deposition of at least two materials, part material and support material. Support material is usually sacrificial and is removed after building is complete. Multi-material deposition systems are designed to fabricate multi-component systems and devices. Another variation is to incorporate a light machining operation (subtractive process) along with the additive process to ensure dimensionality and surface finish. Every added complication to the basic additive LM process imposes a fundamental challenge with the digital representation of process that enables designers to capture the full range of design possibilities offered by LM. LM technology can also be

exploited for depositing structures such as flanges and stiffeners on existing parts and for repairing certain part defects. Key parameters that characterize a LM technique are the build rate and the build envelope, ability to make parts of different materials, dimensional accuracy and feature size.

LAYERED MANUFACTURING TECHNIQUES

A plethora of techniques have been developed during the research phase of LM. The development of each technique probably owes more to inventiveness than to problem-solving. A broad classification of LM techniques based on the nature of the build material that will define the nascent form or shape is given in Table 1. The build materials are classified as liquid, gas, powder, binder, wire or sheet. The main purpose in preparing this list is to highlight the wide variety of concepts involved and the wide variety of materials processed. Brief descriptions of the techniques follow with references for further details.

Table 1. Classification of LM techniques.

LIQUID-based	POWDER-based
<u>Photocurable Slurries</u>	Sintering with Lasers
Curing with UV-Laser	○ Selective Laser Sintering (SLS) - *3D Systems*
○ Stereolithography (SLA) - *3D Systems*	Melting with Lasers
Curing with Visible Light and DMD	○ Laser Eng. Net Shaping (LENS) - *Optomec*
● Direct Photo Shaping (DPS) - *SRI Int.*	○ Laser Additive Mfg (LAM) - *AeroMet*
Curing with light through masks	○ Direct Metal Dep. (DMD) - *POM*
● Microstereolithography (μSLA)- *Lausanne*	
<u>Electrolyte</u>	BINDER-based
Electroplating	Binding Powder
● Electrochemical Fab. (EFAB) - *USC*	○ 3D Printing (3DP) - *Extrudehone/Z Corp*
<u>Drops</u>	Extruding Filament
Printing with Inkjet	○ Fused Dep. Modeling (FDM) - *Stratasys*
○ Multi Jet Modeling (MJM) - *3D Systems*	● Fused Dep. of Ceramics (FDC) - *Rutgers*
○ 3D Plotter - *Solidscape*	● Extrusion Freeform Fab. (EFF) - *ACR*
Casting	
● Shape Deposition Mfg (SDM) - *Stanford*	WIRE-based
● Drop-by-Drop Mfg - *UC-Irvine*	Wire Feed
● Robocasting - *Sandia*	● E-beam Freeform Fab. (EBF^3) *by MIT/NASA*
Freezing Water	
● Rapid Freeze Prototype (RFP) - *Missouri*	SHEET-based
	Lamination
GAS-based	○ Laminated Object Mfg (LOMS) - *Cubic*
Chemical Vapor	
● Laser-asst. CVD (LCVD) - *Georgia Tech*	○ Commercial
Laser	● Research
● Selected Area Laser Dep. (SALD) - *Connecticut*	

Within the LIQUID-based category are build materials such as photocurable slurries, electrolytes and liquid drops. Photocurable slurry techniques vary depending upon the form of energy and level of masking utilized to cure the liquid. *Stereolithography* (SLA) uses a rastered UV laser, *direct photo shaping* (DPS) uses visible light and masks or digital mirror devices and *microstereolithography* (μSLA) uses visible light and masks on the μm-scale. While SLA has achieved commercial status through the efforts of 3D Systems [1], DPS and μSLA, developed by Ventura et al [2] and Beluze et al [3], respectively, are in the research stage. SLA and μSLA are primarily suitable for materials that polymerize, e.g., plastics. With DPS, ceramic parts have been successfully made by binding .the ceramic powder with a photocurable liquid and curing by exposure to light. A novel technique developed by Cohen et al [4] is *electrochemical fabrication* (EFAB), which involves electroplating metallic layers sequentially. Liquid drops make ideal media for precision deposition. Printing with inkjets mimics ink-jet printers, with the ink composed of different kinds of liquids. *Multi-jet modeling* (MJM), marketed by 3D Systems [1], uses multiple ink jets and enjoys increased throughput. The *3D Plotter* is a single ink-jet process and is marketed by Solidscape [5]. Both methods appear to be restricted to a variety of polymeric materials. It must be pointed out that in the case of polymeric materials, the formulations are unique and proprietary and are usually marketed by the system vendor.

Shape deposition manufacturing (SDM), developed by Prinz and Weiss et al [6] uses drops from low-melting wax to high melting metals and alloys to build layered structures with each layer shaped by a suitable machining operation. A variant is Mold SDM [7] in which a ceramic part is gel-cast into a SDM mold usually made of a sacrificial material such as wax. Another interesting method is *drop-by-drop manufacturing* developed by Orme et al [8], which involves directing mono-sized charged drops of liquid metal, generated by an ultrasonic nozzle, to specific locations on a substrate. Research has been restricted to low-melting metals such as solders and aluminum-silicon. *Robocasting*, developed by Cesarano [9], involves depositing drops of water-based ceramic slurries in a predetermined pattern. Leu et al [10] have developed the *rapid freezing prototyping* (RFP) process that freezes water drops into the desired shape. The frozen shape is then used as a pattern for investment casting of metals.

At present, the GAS-based techniques are confined to the laboratory. The principle is to use the thermal energy from a laser to induce a chemical reaction within special reagent gases to produce a solid deposit. Lackey et al [11] have developed *laser-assisted chemical vapor deposition* (LCVD) and Marcus et al [12] have developed *selected area laser deposition* (SALD). There are variations to SALD, in the form of SALDVI, which is vapor infiltration to form a cermet and SALD-Joining, which is joining two ceramic pieces. Gas-based techniques suffer from very low deposition rates, but may have an application involving fabrication of *in situ* sensors such as thermocouples.

POWDER-based techniques appear to have achieved the highest level of commercialization and involve either a powder bed or a powder spray. *Selective laser sintering* (SLS) uses a laser to sinter the uppermost layer on a powder bed in a predetermined pattern. The powder bed is incrementally lowered and the next layer is similarly formed. A sintered shape forms and is supported by the surrounding packed powder. The powder can be a polymer, sand, a ceramic or a metal. For the high melting powder, a binder may be mixed in and, as the laser sweeps the layer, a bound shape emerges. A variation is SLS/HIP in which the outer surface of metallic components is sintered before hot isostatic pressing. Developed by Beaman et al [13], the SLS process is today marketed by 3D Systems [1]. A similar laser-sintering process is EOSINT, which is marketed by Electro Optical Systems [14]. Another powder-based technique

involves feeding powder into a laser melt pool and is mainly applied to metals. In laser additive processes, the reinforced melt pool solidifies into a layer the shape of which is determined by the path followed by the laser beam. Layer-by-layer fusion of such shapes results in a 3D form whose dimensional tolerance, surface finish, microstructure and properties will depend upon how well the processing conditions have been optimized and how accurate a closed-loop control is achieved. *Laser engineered net shaping* (LENS), developed by Griffith et al [15] and marketed by Optomec [16], strives to achieve finer feature size, higher degree of complexity and a smooth surface finish, but at the expense of throughput. To achieve these part attributes requires finer powder and smaller melt pool size. *Laser additive manufacturing* (LAM) is commercialized by AeroMet [17] and involves higher throughput net-shape forming of high-end metallic parts. LAM makes a preform, which is subsequently light machined to the final dimensions and surface finish. *Direct metal deposition* (DMD) was developed by Mazumder et al [18] and is commercialized by Precision Optical Manufacturing [19]. Its claim is a proprietary closed-loop feedback control system for accurate metallic part reproduction.

BINDER-based techniques fall into two categories, binding a powder bed and extruding filaments. The *3D Printing* (3DP) process was developed by Sachs et al [20] and is marketed by a series of licensees such as Z-Corp [21] and Extrudehone [22]. 3DP involves binding the uppermost layers of a powder bed using a series of streams of a suitable binder. The unbound powder provides the support structure. The powder can be a polymer, starch, ceramic or metal. Metallic parts for tooling are fabricated by debinding the printed structure and melt-infiltrating the skeleton with a lower melting alloy to retain part dimensional fidelity. *Fused deposition modeling* (FDM) is marketed by Stratasys [23] and involves the deposition of a binder-containing filament. Danforth et al [24] developed the *fused deposition of ceramics* (FDC) process, which uses ceramic-loaded filaments and the *fused deposition of metals* (FDMet) process, which uses metal-loaded filaments. Proceeding further, a *multi-material deposition* system (FDMM) was developed with the goal of depositing at least two ceramic materials or a metal and a ceramic along with support material. While FDM and FDC involve fabricating carefully formulated filaments and feeding them fused onto the substrate, *extrusion freeform fabrication* (EFF), developed by Vaidyanathan et al [25], involves extruding a binder-ceramic mixture and feeding the filament, unfused, onto the substrate. In all these methods, the green part is later debound and sintered to full density.

WIRE-based SFF involves feeding a metallic wire into a melt pool formed by a laser beam or an e-beam. Preliminary work was done by Eagar et al [26] using a high power e-beam. Recently, Taminger et al [27] have revived the method with their *e-beam freeform fabrication* (EBF^3) process with the goal to develop a fabrication system that could be deployed in a remote setting such as outer space. Advantages of wire feeding are full material utilization and no particulate contamination of the environment, which would be a requirement for space-flight. Finally, in the SHEET-based category is the *laminated object manufacturing* system (LOMS) process marketed by Cubic Technologies [28]. LOMS involves precisely carving out and stacking sheets or laminates made of paper, plastic or bound ceramic using a laser. With the same laser, the support structure is crosshatched and later removed.

By no means is the list in Table 1 complete. However, processes not described would probably fall under one category or the other. While some techniques are dedicated to one material, e.g., LAM or EBF^3 for metals, other techniques can be quite adaptable and have demonstrated capability in fabricating parts from a variety of materials. A listing of some of the commercial rapid prototyping machines, their representative vendors, their capabilities, system

price and materials costs is available on the web [29]. While these machines are capable of fabricating prototypes out of plastic, some of them are designed to fabricate objects and even parts out of metals and ceramics. Prototyping is still the main utility of these commercial systems. Most of the commercial machines are single material systems. Commercial multi-material systems are in the distant future.

MATERIALS AND PROCESSING CHALLENGES

Prior to the advent of layered manufacturing as a fabrication technology, parts were made by processes such as injection molding, powder consolidation, metal casting, gel casting and machining. The materials and processing challenges for these single-step, single material processes were important, but few and relatively straightforward to tackle. For instance, in metal casting, the practitioner had to deal with solidification of liquid metals, in powder metallurgy, consolidation behavior, in injection molding, material flow. LM technologists have to study and understand a host of materials- and process-related issues. A list of these challenges is given in Table 2. Each of these factors can play an important role in the economical manufacture of reliable and functional parts.

Table 2. Materials and processing challenges.

Materials	Process Planning	Processing	Post-processing	Properties
♦ Powders	♦ Tool path	♦ Binding	♦ Debinding	♦ Porosity
♦ Binders	♦ Masking	♦ Curing	♦ Firing	♦ Bonding
♦ Filaments	♦ Road dimensions	♦ Sintering	♦ Co-firing	♦ Shrinkage
♦ Gas precursors	♦ Layer increment	♦ Powder or wire feeding	♦ Resin infiltration	♦ Residual stress
♦ Wires	♦ Preheat	♦ Molten pool forming	♦ Melt infiltration	♦ Distortion
♦ Sheets	♦ Process control • Temperature • Dimension	♦ Solidification	♦ Densification	♦ Dimensional accuracy
♦ Support material		♦ Reaction zone	♦ Heat treatment	♦ Surface finish
♦ Green strength		♦ Gel casting	♦ Machining	♦ Microstructure
				♦ Mechanical properties

Materials issues involve selection of powders, binders, filaments and support with the correct particulate size, shape, formulation, composition, and physical properties. An important factor to consider is the green strength of the part after it is fabricated and before it is densified. Handling issues, among others, will dictate material formulations. Optimized *process planning* for defect-free deposition is important. This involves control of parameters such as tool path, road dimensions, masking, layer increment and, in thermal processes, temperature. Devising optimal trajectories for the deposition head for good inter-road and inter-layer bonding is critical. Designing and fabricating masks optimally is important for precision. Determining the correct conditions for *processing* such as binding, curing, sintering, melting and solidification is important. Determining the correct schedules for *post processing* such as debinding, firing or co-firing, liquid infiltration, densification, heat treatment and light machining are important. Finally, the utility of a part depends on the presence or absence of defects such as porosity, poor bonding,

shrinkage, residual stress and distortion, and *properties* such as dimensional accuracy, surface finish, microstructure and mechanical and other properties.

Understanding materials behavior, whether it be solidification of melted powder or formulation of binder-particulate mixtures, whether it be thermally-induced residual stresses in metals or curing cycles for polymers, is the first step towards reliable fabrication by LM. The next step is to determine processing parameters by experimentation, guided by process models based on prior experience and theories involving heat and fluid flow. For instance, in the case of laser additive processes, Beuth and Klingbeil [30] have developed process maps that link melt pool dimensions with laser power density. Hofmiester et al [31] have developed techniques to visualize the dynamic melt pool and monitor its dimensions and temperature distributions in real time. Combining these two diagnostic tools, active process control is envisioned with the possibility of making metallic parts with high dimensional tolerance and low residual stress. Another example of process development is the anti-alias filtering incorporated in the DPS process by Ventura [32], which turns sharp black and white stair-steps into smooth gray-scale boundaries. Improved surface finish for ceramic parts was demonstrated by achieving a 6-fold reduction in the average stair-step height. Jafari et al [33] developed "tool path based deposition planning" for fused deposition processes. Porosity-free, accurate deposited structures were achieved by a plan involving varying roller (filament feed) speeds. Binder burnout and co-firing are challenges facing multi-material deposition. Allahverdi et al [34] showed that differential expansion caused cracking and delamination in FDMM fabricated PZT tube actuators having helical Ag/Pd electrodes. One solution was to use pre-oxidized metallic powder and deoxidize the electrode after sintering. A pressing need before LM becomes an acceptable manufacturing tool is the characterization of the microstructure and properties of the fabricated part. Rhenium fabricated by LAM was found to be essentially fully dense and reasonably accurate in dimensions, but it had coarse grain size requiring some means of grain refinement such as alloying [35]. Another observation was oxygen pick-up, but this was mainly confined to the surface, which would be ground away. Rhenium is also made by EB-CVD. Grain size and grain orientation have implications for mechanical behavior of shapes such as missile thruster nozzle. EB-CVD will result in grains oriented parallel to the hoop stress formed by the exiting gases, while LAM will result in grains oriented perpendicular to the stress.

THE PROMISE OF LM

Like many new technologies that capture the imagination, LM comes with many promises. A laundry list of benefits, not available with traditional fabrication methods, is touted. The promise of LM falls under three categories: *Unique Fabrication Capabilities, Important Applications and Commercial Implications*. Under unique fabrication capabilities are *avoiding conventional tooling* as there is no need for specialized tooling or part fixturing; *geometric flexibility*, which is the ability to fabricate complex part geometries and arbitrary shapes; and *local composition control*, which is the ability to form graded structures and compositions. Among important applications, LM has made most headway in the fabrication of *prototypes*, a designer's dream. Prototypes are non-functional solid models that are useful visualization aids. LM has made inroads in *machine tooling*, or the fabrication of tools and dies for high volume manufacturing such as injection molding. Manufacturing functional, form and fit *parts and components* is the holy grail for LM. With the transition in manufacturing from *mass production* to *mass customization*, LM is expected to play a major role. It is ideally poised for "lot size of

ONE", or the manufacture of highly individual products, but on a mass scale. With the gradual disappearance of skill-based fabrication, it is expected that LM will *replace handiwork.* There are commercial implications of LM technology. It is suitable for *agile and rapid manufacturing* and has potential to shorten product development time and mitigate logistical problems. Parts can be made *on-demand* instead of having stockpiles of inventory. Through *reverse engineering*, parts whose drawings are not available can be replicated. Through *remote manufacturing*, parts can be made on-board ships, submarines, space station or a remote location. On-line commerce for parts will flourish. Since machining is all but eliminated, an ancillary benefit is less exposure to hazardous material, e.g., lubricants, and less waste, e.g., turnings. It must be recognized that these promises of LM are not mutually exclusive, that two or more of the promises can act simultaneously.

LM has made significant strides in delivering on some of the promises. Sachs [36] gives two examples of *avoiding conventional tooling*. One is extensive use by Bell Helicopter of patterns made of SLA Quickcast for aluminum investment castings purely due to timing, not economic, considerations. The second is SLS-fabricated non-load bearing duraform polyamide parts for Boeing for military applications, which are now under study for certification. An example of *geometric flexibility* is the fabrication of tool dies with conformal-cooling channels. Enhanced heat extraction, increased production rate and reduced cost can thus be achieved. Conformal cooling channels can be made by depositing sacrificial material, which is later removed as with MIT's 3DP process [37], or can be made while fabricating the part as with Optomec's LENS process [16]. Another example of part complexity is the casting for a fuel cross over made for Rocketdyne by Soligen's 3DP process [36]. The *local composition control* capability of LM was demonstrated by cell phone casings made with color printed-in by Z Corp [36] and oral forms of medical "flash dosage" made with drugs in the interior and flavor masking on the exterior by Therics [36]. Both companies use the 3DP technique.

There are many examples of *prototypes*, *tooling* and *parts* made by LM in the literature. The ability to produce conformal cooling channels in tool dies will be a big benefit to the *machine tooling* industry. AeroMet. reports that their LAM-fabricated high-end titanium alloy *parts* are undergoing certification by the aerospace community [38]. A recent issue of The Economist magazine [39], defined *mass customization* as building to meet customer's individual orders rather than for stock. The goal is to deliver precisely the system that the customer wants and when he wants it. LM is poised to contribute to the mass customization or "build-to-order" concept. As an illustration of mass customization, Sachs [36] gives the example of plastic aligners for orthodontic work marketed by Align Technology. A sequence of plastic aligners, instead of wire braces, are used to move teeth. The aligners are thermoformed on molds of sequential models made by 3D Systems' SLA technique. The sequential models are computer-generated for teeth reorientation and are based on the initial plaster cast of the rubber impression of the crooked teeth. Conventionally, the aligners are milled, but details in regions where the teeth meet are best achieved by LM. An example of *replacing handiwork* is the hearing aid [36]. In conventional practice, substantial manual skill is needed to go from the rubber model to the final hearing aid. But, with the disappearance of these skills, these parts can now be built by LM. From a virtual model of the inner ear, Siemens Corporation created a shell by SLS. Electronics were later added to the shell to create the finished product.

Fabrication of spare parts and reproduction of components for which there is no engineering data are important benefits for several industries, especially the military. This *reverse engineering* concept is demonstrated by Anderson et al [40], who are adapting the 3DP

technique to fabricate metallic components. The plan is to start with an original component, perform a CT scan on it, generate the 3D data files, send it over the internet to a 3DP machine such as that marketed by Prometal, which produces a functional replica of the original part. Issues relating to reliable data transfer, logistics and internet security will have to be dealt with. The *remote manufacturing* promise of LM is being explored by the US Army TACOM division to produce replacement parts on demand in the field. For this purpose, the "Mobile Parts Hospital" program was conceived. The rapid manufacturing system consists of a LENS station for fabrication of metal parts and a multitask machining center to meet surface finish and tolerance requirements [41].

LM OPPORTUNITIES

It is recognized that progress is being made and will continue to be made towards realizing the promise of LM. However, LM is continuously evolving. While the bulk of the development work has been done in making single material, monolithic parts and objects for prototype and structural applications, programs exploiting the multi-material capability of LM are progressing. One goal is to develop functional and multi-functional materials with minimum post-processing. A multi-functional material could serve a dual purpose, e.g., structural and energy storage. Another goal is to fabricate systems with minimal assembly. Steps such as marking, drilling and soldering are time consuming and with every additional step in the manufacturing cycle the probability of defects and errors increase. With LM, "plug-and-play" modules can be readily made for modular devices. Minimizing assembly results in compact, lightweight, reliable and economical systems. Multi-material deposition machines, such as Rutgers' FDMM [42], are on-line and being utilized as experimental tools to manufacture a variety of functional parts. Opportunities for research are in the *biomedical engineering*, *electronics* and *sensor* areas, in the development of *hybrid manufacturing* systems and in *nanomanufacturing*.

In the *biomedical engineering* field considerable headway has been made in the orthopedic tissue engineering area. Strong scaffolds for bone growth having controlled porosity and made of bio-compatible polymers have been fabricated with techniques such as MIT's 3DP [20], Rutger's FDC [24] and ACR's EFF [25]. It is conceived that the scaffold will be in the shape of the degenerated or damaged bone, such as a broken jaw. The scaffold is impregnated with osteoinductive material to produce a polymer-calcium phosphate composite blend. After implantation, bone would replace the blend. In the *electronics* field, the goal is to replace the step-intensive tape casting/screen printing process of making MCMs with direct deposition of the individual passive and active components, the interconnects and the surrounding packaging media. Resistors, capacitors, conductors, through connections, all made of appropriate materials, are deposited, layer-by-layer, to achieve 3D device integration. It is envisaged that thermoelectric and other sensors, EMI shielding and heat sinks can also be integrated following a given design concept. Progress has been made with techniques such as NRL's MAPLE DW [43] by which a variety of electronic elements were accurately deposited on substrates and TA&T's stereo-photolithography [44] by which fully dense, narrow silver lines were deposited on ceramic substrates. The goal is to develop an automated process for electronic packaging having high resolution and high level of integration. A major scientific issue with multi-material deposition is determining the optimum densification (co-firing) conditions for defect-free and reliable components. In the *sensor* area, Li and Prinz [45] demonstrated embedding of optical

fiber in a structural element. The ability to continuously monitor structural health using embedded sensors would be very beneficial indeed.

Hybrid manufacturing processes utilize additive/subtractive operations such as Stanford's SDM [7]. Part quality, e.g., surface finish, is enhanced. Parts with internal channels such as miniaturized fuel cells and microfluidic devices are possible. Other permutations could involve a combination of techniques such as laser deposition and electroplating [45] or combining with MEMS and VLSI to realize products in the meso-scale regime. The ultimate goal is *integrative product synthesis*. Now that nanotechnology is here to stay, attention has shifted to *nanomanufacturing*. Cost effective, high throughput nanomanufacturing is the goal. Techniques such as Mirken et al's [46] dip-pen nanolithography (DPN), which involves depositing material via molecular transport using an AFM tip, and Chou et al's [47] nano imprint lithography (NIL), which involves imprinting by mold pressing and pattern transfer are being explored to realize this goal. Both approaches are ideally suited for layer-by-layer fabrication and would benefit from the LM concept of CAD-based intelligent manufacturing. It must be cautioned that in the nanometer world, gravity becomes negligible and surface tension, electrostatic and Van der Waals forces come into play, which will have implications for deposition and manipulation at the nano-scale. It is hoped that a multi-instrument (deposition-removal) machine possible with LM technology could be built to achieve fabrication, inspection, measurement and certification necessary for robust nanomanufacturing.

SUMMARY

A multitude of LM techniques has been described. Some have achieved commercial status, others are still in the laboratory stage. The aerospace, automotive, defense, electronics, and biomedical fields are poised to benefit from LM. LM is compatible with all classes of materials - metals, ceramics, polymers, composites, organics, and biomaterials. With this compatibility comes a host of materials and processing issues and challenges. Progress has been made to assuage some of these challenges. The current status of LM is that the science and engineering is mostly understood, however material properties such as microstructure and performance need to be documented thoroughly. For LM to achieve manufacturing status, full automation is a must, fabrication speed needs to be enhanced and engineering properties need to be measured and certified. LM is multi-disciplinary, involving manufacturing, robotics, mechanical, materials, information technology, computer science, chemistry, biomedical and electronics. It begs a system's approach. LM comes with many promises - avoiding conventional tooling, geometric flexibility, local composition control, mass customization, agile manufacturing, remote manufacturing and reverse engineering. Significant strides have been made in fulfilling some of these promises. Opportunities in LM are in bone scaffolds, 3D device integration, hybrid manufacturing and lithography-based nanomanufacturing.

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